ELSEVIER
25 October 2001
PHYSICS LETTERS B
Physics Letters B 519 (2001) 46–49
www.elsevier.com/locate/npe

Study of system-size effects in multi-fragmentation using quantum molecular dynamics model

Jaivir Singh [a], Rajeev K. Puri [a], Jörg Aichelin [b]

[a] *Department of Physics, Panjab University, Chandigarh 160 014, India*
[b] *SUBATECH, Ecole des Mines de Nantes, 4 rue Alfred Kastler, F-44070 Nantes cedex, France*

Received 1 March 2001; accepted 6 June 2001
Editor: J.-P. Blaizot

Abstract

We report, for the first time, the dependence of the multiplicity of different fragments on the system size employing a quantum molecular dynamics model. This dependence is extracted from the simulations of symmetric collisions of Ca + Ca, Ni + Ni, Nb + Nb, Xe + Xe, Er + Er, Au + Au and U + U at incident energies between 50 *A* MeV and 1 *A* GeV. We find that the multiplicity of different fragments scales with the size of the system which can be parameterized by a simple power law.

PACS: 25.70.Pq; 24.10.Lx
Keywords: Multi-fragmentation; Quantum molecular dynamics model; System size effects; Heavy ion collisions

The breaking of colliding nuclei into dozen of fragments has been a central topic both in experimental and theoretical nuclear physics research. The theoretical interests have been concentrated on the understanding of the reaction mechanism behind fragmentation. One has also tempted to look for the role of in-medium cross section and nuclear equation of state in fragmentation. These studies have been carried out by analyzing the fragment multiplicity and their kinetic energy spectra using heavy target/projectile [1–4,6]. However, a very little attention has been paid to the system size effects in multi-fragmentation although it may not only explore the effect of ratio of surface to volume in fragmentation, but can also throw the light on the dynamical effects which are expected to increase with the increasing size of the system.

Recently, the FOPI Collaboration [3] analyzed the system size effects in fragmentation by studying the reactions of Ni + Ni, Ru + Ru, Xe + CsI and Au + Au. They analyzed the spectra by dividing the interacting matter into spectators and participants. The spectator fragments show the well-known universality [1] whereas the intermediate mass fragments emitted from the participant source scale with the size of the emitting source indicating the role of the expansion of the matter in multi-fragmentation. The role of the expansion has already been established in collective flow [7].

Motivated by these findings, we present here, for the first time, a complete study of the dependence of the fragment multiplicity on the size of the colliding (symmetric) nuclei by studying the reactions of different nuclei with masses ranging between 40 and 238. We shall show that the multiplicity of all kinds of frag-

E-mail addresses: j_thanua@yahoo.com, j_thanua@hotmail.com (J. Singh), rkpuri@pu.ac.in (R.K. Puri).

PII: S0370-2693(01)01073-5

ments scales with the size of the system which can be parameterized by a simple power law $\propto A_{\rm tot}^{\tau}$ ($A_{\rm tot}$ is the mass of the composite system) at all incident energies and impact parameters.

A word of caution should be added here: it has been shown and discussed extensively in the literature that the mass yield curve approximately obeys a power law behavior $\propto A^{-\tau}$ [2,4]. It has been conjectured (though controversial) that this behavior is an indication of the phase transition between a gaseous and liquid phase of the nuclear matter. This power law behavior obtained for the mass or charge distribution is for a "*given system*". The power law dependence, which we are talking about, is something very different. We shall show that the multiplicity of a given fragment (or a group of fragments) scales with the size of the interacting system which can be parameterized in terms of a power law function.

The basis of our investigation is a quantum molecular dynamical (QMD) model [4], where nucleons interact via two- and three-bodies which preserves the particle correlation and fluctuations. Here, each nucleon is represented by a Gaussian wave packet with width $\sqrt{L}$ centered around the mean position $\vec{r}_i(t)$ and the mean momentum $\vec{p}_i(t)$:

$$\phi_i(\vec{r},\vec{p},t) = \frac{1}{(2\pi L)^{3/4}} e^{[-(\vec{r}-\vec{r}_i(t))^2/4L]} e^{[i\vec{p}_i(t)\cdot\vec{r}/\hbar]}. \tag{1}$$

The Wigner distribution of a system with $(A_T + A_P)$ nucleons is given by

$$f(\vec{r},\vec{p},t) = \sum_{i=1}^{A_T+A_P} \frac{1}{(\pi\hbar)^3} e^{[-(\vec{r}-\vec{r}_i(t))^2/2L]} \times e^{[-(\vec{p}-\vec{p}_i(t))^2 2L/\hbar^2]}. \tag{2}$$

We shall use here a static soft equation of state along with energy dependent nucleon–nucleon cross section. The detail discussion about the different equations of state and cross sections can be found in Ref. [4]. We follow the nucleons till 300 fm/c and then freeze their coordinates. This time is long enough to assume that the reaction has finished. The frozen phase space of nucleons is, then, clusterized to obtain the fragments. The clusterization is performed within minimum spanning tree (MST) method which binds two nucleons in a fragment if they are closer than 4 fm.

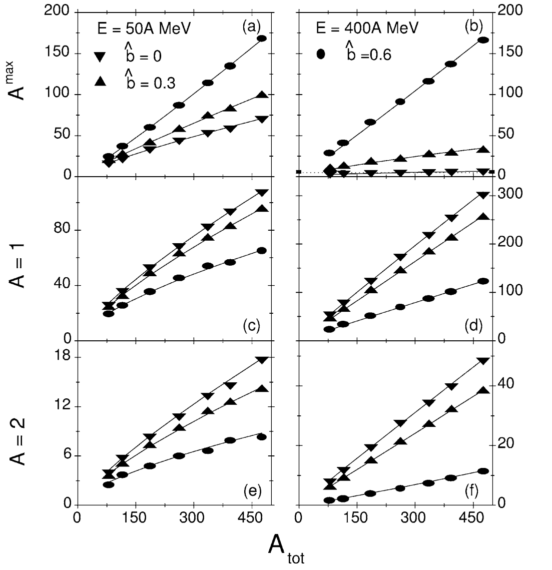

Fig. 1. The heaviest fragment $A^{\rm max}$, the multiplicity of free-nucleons and fragments with mass $A = 2$ as a function of composite mass of the system $A_{\rm tot}$ $(= A_T + A_P)$ at different scaled impact parameters $\hat{b}$. The left-hand side is at 50 A MeV whereas right-hand side is at 400 A MeV. The displayed results are at 300 fm/c.

Here we simulate several thousand events involving the different symmetric colliding nuclei like ^{40}Ca + ^{40}Ca, ^{58}Ni + ^{58}Ni, ^{93}Nb + ^{93}Nb, ^{131}Xe + ^{131}Xe, ^{168}Er + ^{168}Er, ^{197}Au + ^{197}Au and ^{238}U + ^{238}U at incident energies between 50 A MeV and 1 A GeV and at different impact parameters $\hat{b} = b/b_{\rm max}$; $b_{\rm max} = R_1 + R_2$, R_i is the radius of target/projectile. By varying the size of the symmetric system, the system size effect can be studied without varying the asymmetry and excitation energy of the reaction. Note that the ALADIN experiment varies the asymmetry of a reaction [1] whereas the FOPI experiments are for symmetric nuclei [3]. The wide range of incident energy between 50 A MeV and 1 A GeV gives us possibility to study the multi-fragmentation in regions where different reaction mechanisms have been proposed [6].

In Fig. 1, we display the largest remnant, the number of emitted nucleons and light fragments with mass = 2 at 50 and 400 A MeV. The multiplicity of the light mass fragments (LMF's) $2 \leqslant A \leqslant 4$, the medium mass fragments (MMF's) $3 \leqslant A \leqslant 14$ and the intermediate mass fragment (IMF's) $5 \leqslant A \leqslant \min[A_{\rm tot}/6, 65]$ is displayed in Fig. 2. Note that the MMF's and IMF's excludes the heaviest fragment.

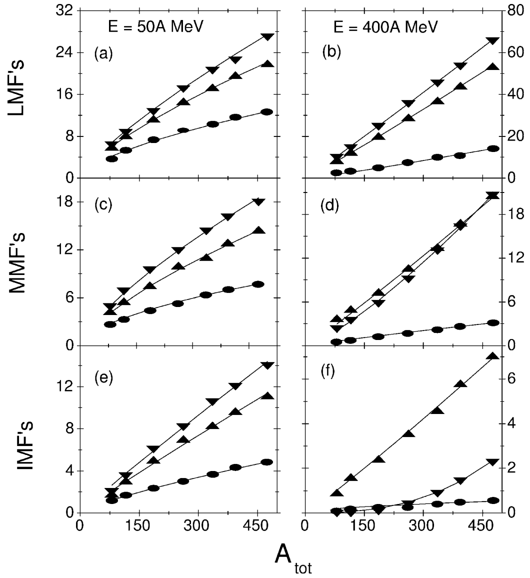

Fig. 2. Same as Fig. 1, but for light mass fragments (LMF's) ($2 \leqslant A \leqslant 4$), medium mass fragments (MMF's) ($3 \leqslant A \leqslant 14$) and intermediate mass fragments (IMF's) ($5 \leqslant A \leqslant \min[1/6A_{\text{tot}}, 65]$).

The general behavior of all fragments follows the well-known trends. In peripheral collisions ($\hat{b} = 0.6$), the largest fragment $A^{\max}$ follows roughly the reaction geometry insofar the nonoverlapping nucleons for the largest remnant. The size of the heaviest fragment scales with the size of the spectator matter which depends on the size of the interacting system. The light charge particles (i.e., the emitted nucleons, the fragment with mass = 2 and LMF's) follow the same trend at all incident energies. Their multiplicity is maximum at $\hat{b} = 0$ and which is followed by $\hat{b} = 0.3$ and 0.6. The emission of the light charge particles depends on the size of the participants which decreases with the decrease in the overlapping volume. One also sees that the number of light charge particles emitted at 50 A MeV is much smaller than at 400 A MeV. Most of the matter at higher incident energies (i.e., at 1 A GeV) is in the form of light charge particles. At higher incident energies, the nucleon–nucleon collisions (with large momentum transfer) destroy the correlation in the participant matter and only light particles survive from the reaction zone. At lower incident energies, most of the collisions are Pauli blocked and therefore, many nucleons in the reaction zone survive the reaction without suffering collisions with a large momentum transfer. The energy received by a target in peripheral collisions is not enough to excite the matter far above the Fermi level, therefore, a heavier largest fragment $A^{\max}$, and small number of nucleons/LMF's and MMF's are emitted at peripheral collisions ($\hat{b} = 0.6$). We also see that the maximum production of medium mass and intermediate mass fragments occurs for $\hat{b} = 0$ at 50 A MeV which shifts towards $\hat{b} = 0.3$ at 400 A MeV [1,4]. With increasing incident energy, the multi-fragmentation becomes more and more a phenomenon of peripheral reaction. Due to larger overlap between the colliding nuclei at $\hat{b} = 0$, the excitation in the system at 400 A MeV does not allow the formation of heavier fragments, therefore, we see small number of MMF's and IMF's. The situation improves at $\hat{b} = 0.3$. At peripheral collisions ($\hat{b} = 0.6$), the amount of excitation, compression and nucleon–nucleon collisions decreases and therefore, heavier residual fragment survives.

The most interesting outcome of Figs. 1 and 2 is that in all cases, independent of the mass of the fragment, incident energy (and excitation energy) and impact parameter, the heaviest fragment and the multiplicity of all kind of fragments (i.e., of nucleons, light, medium and intermediate mass fragments) scales with the size of the system which can be nicely parameterized by a power law $= c \cdot A_{\text{tot}}^{\tau}$; A_{tot} is the mass of composite system. The values of constants c and τ depend on the size of the fragment and on the incident energy and impact parameter of the reaction. The dependence of the power factor τ on incident energy and impact parameter is displayed in Fig. 3. We also tried a function form $C \cdot e^{-\tau A}$, but fits were worse than obtained with a power law. It is worth mentioning that a similar power law dependence is also obtained for other groups of fragments like $5 \leqslant A \leqslant 25$. The power law was also obtained at other incident energies $E = 100, 200, 600$ and 1000 A MeV indicating the universality of the power law behavior for system size effect in multi-fragmentation/clusterization.

In Fig. 3, we plot the value of τ as a function of the reduced impact parameter $\hat{b}$ at incident energies 50 and 400 A MeV. The different panels of the figures are, respectively, for heaviest fragments $A^{\max}$, free nucleons, fragments with mass 2, LMF's, MMF's and IMF's. We see that the value of the τ in most of the cases depends weakly on the impact parameter. The value of τ increases with the incident energy and then saturates for very high energies. It is close to 2/3 at

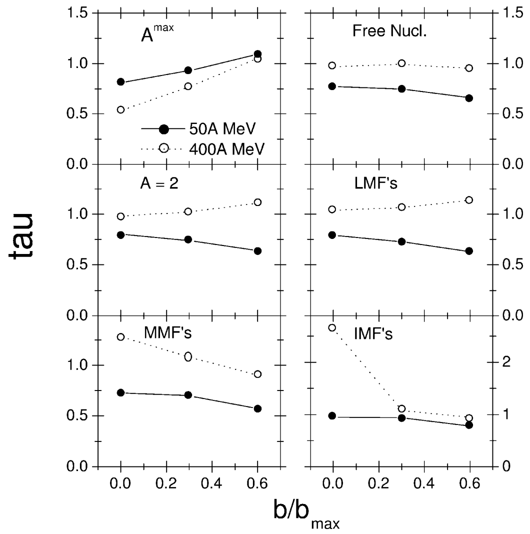

Fig. 3. The τ as a function of the reduced impact parameter $\hat{b}$. The solid and dashed lines shows, respectively, the results at 50 and 400 *A* MeV.

50 *A* MeV whereas it is ≈ 1 at 400 *A* MeV. The only exception in this trend is the value of τ $(= 2.6)$ for IMF's at 400 *A* MeV and $\hat{b} = 0$. This exception is rather linked with the mass range used to define an IMF. The lower mass limit of an IMF is 5 units and from Fig. 1(b), we see that the $A^{\max}$ in this reaction fluctuates around 5 for heavier colliding nuclei which may lead to the emission of few intermediate mass fragments. These fragments cause a large value of τ.

We also notice that unlike the disappearance of flow (where the energy of vanishing flow varies as $A^{-1/3}$) [5], no unique dependence on τ exists. This behavior of τ demonstrates that the degree of clusterization is more for heavier colliding nuclei which could be attributed to the fast decompression of the system in heavier nuclei at central collisions. Similar trends are also reported by the FOPI Collaboration [3]. If one plots the reported results of FOPI experiments [3] as a function of size of the system, a similar power-law fit can also be obtained [3]. Here one should keep in the mind that the analysis of FOPI experiments is done for participant region only. Our present result includes both the participant and spectator regions. It is worth mentioning that the value of τ may depend on the clusterization model one is using. As has been noted in Ref. [3], this scaling of the multiplicity of fragments with total mass of the system, draws two important aspects: (i) the role of the surface to volume ratio in clusterization and (ii) the dominance of the expansion following the compression over the competition between the attractive mean field and repulsive Coulomb force in multi-fragmentation. The increase in the multiplicity of the fragments with mass of the system points toward the fact that the expansion of the compressed matter is much faster in heavier systems compared to lighter systems.

Summarizing, using quantum molecular dynamics (QMD) model, we find, for the first time, a power-law behavior for the system-size effect in fragmentation at all incident energies between 50 *A* MeV and 1 *A* GeV and for all colliding geometries. This dependence exists for any kind of fragment/group of fragments and can be parameterized in terms of a power law.

Acknowledgements

This work was supported by Council of Scientific and Industrial Research grant No. 03 (0823) /97/EMR-II.

References

[1] A. Schüttauf et al., Nucl. Phys. A 607 (1996) 457, and references therein.
[2] C. Williams et al., Phys. Rev. C 55 (1997) R2132;
Y.G. Ma, W.Q. Shen, Phys. Rev. C 51 (1995) 710.
[3] W. Reisdorf, in: Proceedings of International Workshop, XXVII, on Gross-properties of Nuclei and Nuclear Excitations, Vol. XXVII, 1999, p. 82;
B. de. Schauenburg et al. GSI scientific report 98-1, 1998, p. 56.
[4] J. Aichelin, Phys. Rep. 202 (1991) 233;
S. Kumar, Ph.D. Thesis, Panjab University, Chandigarh, India, 1999;
Ch. Hartnack, Ph.D. Thesis, University of Frankfurt, Germany, 1989;
G. Peilert, H. Stöcker, W. Greiner, A. Rosenhauer, A. Bohnet, J. Aichelin, Phys. Rev. C 39 (1989) 1402.
[5] D.J. Magestro et al., Phys. Rev. C 61 (2000) 021602(R).
[6] P.B. Gossiaux, J. Aichelin, Phys. Rev. C 56 (1997) 2109.
[7] S. Jeong, FOPI Collaboration, Phys. Rev. Lett. 72 (1994) 3468;
S. Jeong, FOPI Collaboration, Phys. Rev. Lett. 189 (1988).